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Cosmogenic radionuclide dating of glacial landforms in the Lahul Himalaya, northern India: defining the timing of Late Quaternary glaciation

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ABSTRACT: The timing of glaciation in the Lahul Himalaya of northern India was ascertained using the concentrations of cosmogenic ^{10}Be and ^{26}Al from boulders on moraines and drumlins, and from glacially polished bedrock surfaces. Five glacial stages were identified: Sonapani I and II, Kulti, Batal and Chandra. Of these, cosmogenic exposure ages were obtained on samples representative of the Batal and Kulti glacial cycles. Stratigraphical relationships indicate that the Sonapani I and II are younger. No age was obtained for the Chandra glacial advance. Batal Glacial Stage deposits are found throughout the valley, indicating the presence of an extensive valley glacial system. During the Kulti Stage, glaciers advanced ca. 10 km beyond their current positions. Moraines produced during the Batal Stage, ca. 12–15.5 ka, are coeval with the Northern Hemisphere Late-glacial Interstadial (Bølling/Allerød). Deglaciation of the Batal Glacial Stage was completed by ca. 12 ka and was followed by the Kulti Glacial Stage during the early Holocene, at ca. 10–11.4 ka. On millennial time-scales, glacier oscillations in the Lahul Himalaya apparently reflect periods of positive mass-balance coincident with times of increased insolation. During these periods the South Asian summer monsoon strengthened and/or extended its influence further north and west, thereby enhancing high-altitude summer snowfall. Copyright © 2001 John Wiley & Sons, Ltd.

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KEYWORDS: cosmogenic radionuclide dating; glaciation; Himalayas; Late Quaternary; South Asian summer monsoon.

Introduction

Mountain glaciers, because of their relatively small size, are especially sensitive to changes in local climate. Mapping and dating the landforms produced by the episodic advance and retreat of glaciers provide a method for reconstructing local climate oscillations. A detailed reconstruction of local climate oscillation in turn provides a means for exploring the relationship between local and global climate changes.

The dynamics of the Himalayan mountain glaciers are influenced by global temperature cycles, which relate to variations in both the South Asian monsoon and in the mid-latitude westerlies. These two climatic systems have had a profound effect on Himalayan glaciers throughout Late Quaternary times. Benn and Owen (1998) speculated that, during the last glacial cycle, glaciations were not synchronous throughout the region and that in some parts of the Himalayas glaciers reached their maxima during the global glacial maximum of ca. 18–20 ka, whereas in other regions glaciers were most extensive between ca. 30 and 60 ka. However, the paucity of a detailed chronology for these glacial cycles has made this hypothesis difficult to test.

The scarcity of chronologies for this region mainly results from the lack of organic material suitable for ^{14}C dating within, or associated with, glacial deposits and landforms. Relatively new techniques, however, especially optically stimulated luminescence (OSL) dating and cosmogenic radionuclide surface exposure dating, are useful for reconstructing the timing of glaciation within several regions of the Himalayas (e.g. Sharma and Owen, 1996; Sloan *et al.*, 1998; Phillips *et al.*, 2000; Richards *et al.* 2000a,b; Taylor and Mitchell, 2000).

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In this paper, we use cosmogenic radionuclide surface exposure dating to ascertain the timing of glaciation at the end of the Pleistocene and during the early Holocene in the Lahul Himalaya. Using these data we investigate the linkage between regional and global climate.

The Lahul Himalaya was chosen because it contains impressive moraines and glacially eroded landforms produced during at least three glacial stages. These well-preserved geological archives are a near ideal setting for delineating the nature of Late Quaternary palaeoclimate change in the Himalayas (Owen *et al.*, 1995, 1996, 1997) (Plate 1 and Table 1). The Lahul Himalaya, located at the junction of the monsoon-influenced Pir Panjal Mountains of the Lesser Himalaya and the semi-arid mountains of the Trans-Himalaya, is ideally suited for examining the importance of two competing weather systems: the south Asian summer monsoon and the mid-latitude westerlies. The region presently receives most of its precipitation as winter snow (Mamgain, 1975; Owen *et al.*, 1995), supplied by the mid-latitude westerlies that bring moisture from the Mediterranean, Black and Caspian Seas. Little precipitation falls during the summer because orographic shielding by the Pir Panjal Mountains blocks the summer monsoon from reaching the Lahul Himalaya. However, during strong monsoon years, such as that of 1996, heavy rainfall can occur throughout the Chandra valley, at the southern end of the Lahul Himalaya, and even to elevated regions as far north as Chandra Tal and the Bhaga valley. The data presented here allow us to test the specific hypothesis that throughout the Quaternary glacier fluctuations in the Lahul Himalaya reflect changes in the mid-latitude westerlies and the south Asian summer monsoon.

Methods

The relative glacial chronology established by Owen *et al.* (1995, 1996, 1997: Table 1) was used as a framework for selecting areas in which to collect rock samples for cosmogenic radionuclide exposure age dating. The relative ages of the successively older Kulti, Batal and Chandra moraine sequences were established using standard morphostratigraphical techniques similar to those described in Rose and Menzies (1996). Exposure ages of the glacial features were determined by utilising cosmic-ray-produced ^{10}Be and ^{26}Al. We collected rocks having quartz-rich lithologies (granite, quartzite and vein quartz) in three different geomorphological settings (Fig. 1): boulders from the crests of lateral and latero-frontal moraines, boulders from the crests of drumlins, and boulders and bedrock from ice-polished surfaces. Samples were selected to minimise the likelihood of displacement or toppling since the time of emplacement. In order to test the effectiveness of our sampling procedure, we determined ages of multiple samples from each glacial stage. The reproducibility of the results confirms the validity of the exposure ages and gives an indication of the associated uncertainty.

As the dates obtained using the cosmogenic radionuclide technique for this particular study will be compared to the global records based on other chronometry it is essential that all systematic errors in the cosmogenic radionuclide ages be considered. These errors can be classified either as physics-based, i.e. relating to production rates, or geological in nature. Both of these uncertainties generally are greater than the measurement accuracy, which can be $< 5\%$.

The production rate of ^{10}Be or ^{26}Al by energetic particles at Earth's surface is given by equations in Stone *et al.* (1998a) and in Granger and Smith (2000). In the case of no erosion, these equations simplify to equation (1)

$$N_i(z) = [(P_{n,i}\tau_i) + (Y_i A_1 + Y_i A_2)\tau_i](1 - e^{-t/\tau_i}) \quad (1)$$

This equation includes production by secondary neutron spallation and by stopped muons. The subscript i denotes either ^{10}Be or ^{26}Al, $P_{n,i}$ denotes production by neutron spallation at the surface, τ_i is the radioactive mean life ($\tau_{26} = 1.02$ Myr; $\tau_{10} = 2.16$ Myr). Values for the muon related parameters Y_i, A_1, A_2, L_1 and L_2 are given in Granger *et al.* (2001). ^{10}Be and ^{26}Al are also produced by fast muons. Production via this mechanism is negligible in all but the most rapidly eroding samples. At sea-level and high latitudes spallation accounts for ca. 97% of the ^{10}Be and ^{26}Al production at the surface of a rock; negative muon capture and fast muon reactions for only ca. 3% (Heisinger, 1998; Heisinger and Nolte, 2000). The relative importance of muon production decreases to less

Table 1 Summary of Owen *et al.*'s (1995, 1996, 1997) glacial chronology for the Lahul Himalaya

Glacial stage	Characteristics	Type of glaciation	Age
Sonapani	Two sets (Sonapani I and II) of small sharp-crested moraines within a few kilometres of the contemporary glaciers	Limited glacial advances	No dates on Sonapani I, but thought to be early to mid-Holocene. Sonapani II is historical
Kulti	Well-developed moraines in tributary valleys that stretch up to 12 km from the contemporary glaciers. The moraines comprise multiple ridges	Valley glaciation within tributary valleys. Glaciers only just extending into the main trunk valleys	Radiocarbon date of 9160 ± 70 yr BP on the base of a peat bog within a moraine depression
Batal	Highly weathered and dissected lateral moraines and drumlins that extend along the Bhaga and Chandra valleys down to an altitude of ca. 2700 m. Two substages (Batal I and II) can be recognised on the basis of superimposed drumlins and complex moraine successions	Main trunk valley glaciation	OSL dates of 43.4 ± 10.3 ka and 36.9 ± 8.4 ka on deltaic deposits thought to have formed during deglaciation
Chandra	Glacially polished and streamlined bedrock benches with erratics and eroded drumlins at altitudes of >4300 m a.s.l.	Broad valley glaciation	No dates

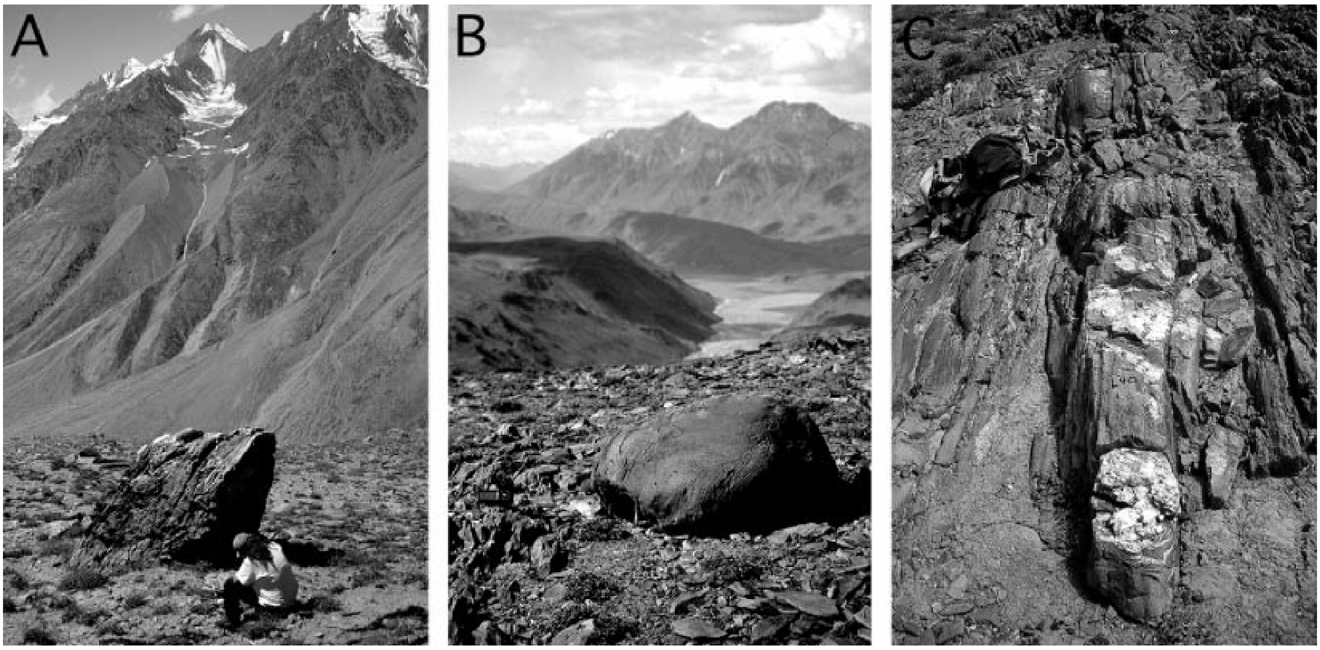

Figure 1 Typical sampling locations for cosmogenic radionuclide dating. (A) A glacial boulder (sample L37) on a lateral moraine of Batal Glacial age near the top of the Kunzum La. (B) A metre-size glacial boulder (sample L42) on an ice-polished bedrock surface above the Kunzum La. (C) Ice-polished bedrock (sample L40) above the Kunzum La

than 1.5% at the 2500 to 4800 m exposure elevation of the surfaces dated in this paper.

The production rate of a nuclide, $P_{n,i}$, is a function of altitude and latitude (Lal and Peters, 1967; Lal, 1991), reflecting changes in atmospheric and geomagnetic shielding, respectively. Production rates usually are quoted at sea-level and high latitude (SLHL) because such scaled values are independent of geomagnetic field intensity. Spallogenic production rates can be scaled from SLHL reference values to sample altitude and geographical latitude using table 2 of Lal (1991). Recently, Dunai (2000) has re-evaluated latitude and altitude scaling factors to take account of non-dipole components in the geomagnetic field and deviations from the normally used universal pressure–altitude relationship for the atmosphere. Use of Dunai's scaling factors yields present-day cosmogenic radionuclide production rates that are ±5% different at our Lahul sites than those calculated from Lal (1991). As the correction is small and because it is not clear how to account for temporal variations of Dunai's correction factors we use the scaling factors from Lal (1991). Production by stopped muons has been scaled for elevation using an attenuation length of 247 g cm^{-2} and for latitude assuming the same sea-level variation for stopped muons as for neutrons (Stone *et al.*, 1996).

Over the past 60 kyr the geomagnetic field intensity has fluctuated by almost a factor of four (Guyodo and Valet, 1996), producing long-term changes in the production rate. The effect of this change on radionuclide production can be expressed as an equivalent change in geomagnetic latitude. Nishiizumi *et al.* (1989) expresses this relationship as

$$\cos(\lambda_{\mathrm{eff}}) = (M_t/M_0)^{1/4}\cos(\lambda_0) \quad (2)$$

where λ_{eff} is the effective geomagnetic latitude for the changed field intensity, M_t is the geomagnetic field intensity at t, M_0 the current field intensity, and λ_0 the current geomagnetic latitude. Using equation (2) we calculate the effective geomagnetic latitudes using the sin*t*200 intensity record of Guyodo and Valet (1996). Radionuclide decay has been accounted for by weighting the effective geomagnetic latitudes by $e^{-t/\tau}$, with τ being the nuclide mean-life. For samples considered in this study, the maximum correction to the exposure age is 3%. Samples L24 and L25 have larger corrections but their ages are anomalously young because of deep weathering and exfoliation.

We use a SLHL spallogenic production rate of $P_n =$ 5.2 atoms g^{-1} yr^{-1} for ^{10}Be and $P_n = 31.2$ for ^{26}Al for the exposure age calculations in this paper. When corrected for time variation in the geomagnetic field, as described above, this value increases to 5.4 atoms g^{-1} yr^{-1}. This SLHL production rate for ^{10}Be is the 13 000 yr rescaled measurement from glacial surfaces in the Sierra Nevada (Nishiizumi *et al.*, 1989; Clark *et al.*, 1995). This production rate is consistent with that determined on the 9800 yr Köfels landslide (Kubik *et al.*, 1998). The $^{26}Al/^{10}Be$ production ratio is taken to be 6.03 ± 0.31 (Nishiizumi *et al.*, 1989).

Apart from uncertainties in the production rates there are geological uncertainties associated with using cosmogenic dating techniques on glacial moraines. Boulders on crests of lateral and latero-frontal moraines are formed as glaciers advance and deposit till by meltout, mass movement and ice-deformational processes. Previous workers have assumed that the construction of moraines is rapid because climate variability is relatively short (decadal to millennial) in duration. In these circumstances cosmogenic radionuclide exposure ages of boulders on moraine crests provide reliable dates on the timing of glaciation (Gosse *et al.*, 1995a,b; Phillips *et al.*, 1996, 2000). However, large lateral and latero-frontal moraines in Himalayan environments may have a long, complex history and may represent longer periods of formation that conceivably can last many millennia (Scott, 1992). In such cases boulders collected from the highest proximal moraines may be more representative of the last stage of a glaciation; indeed they may be almost equivalent to the age of deglaciation. This probably is the case with the thick moraines of the Batal Glacial Stage. The smaller, generally single-crested moraines of the Kulti Glacial Stage (Fig. 2C) probably were formed over a short period (decadal to centennial time-scales) and cosmogenic radionuclide exposure ages of boulders resident on their crests

Table 2 Cosmogenic radionuclide data

Sample number	Latitude (°N)	Longitude (°E)	Altitude (m)	Shielding	Sample mass (g)	Be (mg)	Al (ppm in quartz)	Al Carrier (mg)	^{10}Be/^{9}Be (atoms/atoms 10^{-15})	^{10}Be (10^6 atom/g)	^{26}Al/^{27}Al (atoms/atoms 10^{-15})	^{26}Al (10^6 atom/g)
L7	32.4	77.6	4340	1	7.266	0.446	258		225 ± 15	0.922 ± 0.062	868 ± 60	4.98 ± 0.34
L8	32.5	77.6	4350	1	20.032	0.359	171		925 ± 32	1.110 ± 0.039	1680 ± 82	6.40 ± 0.31
L9	32.5	77.6	4350	1	20.267	0.355	111		885 ± 41	1.035 ± 0.047	2631 ± 72	6.50 ± 0.18
L10	32.3	77.2	2390	0.99	12.534	0.355	1440		158 ± 12	0.298 ± 0.023	66.2 ± 6.9	2.12 ± 0.22
L12	32.3	77.2	2415	0.99	29.684	0.370	8.22	2.269	330 ± 11	0.275 ± 0.009	842 ± 52	1.64 ± 0.10
L15	32.3	77.2	2430	0.99	37.096	0.366	18.0		633 ± 19	0.419 ± 0.013	542 ± 37	0.217 ± 0.015
L20	32.6	76.9	2865	0.90	7.722	0.366	17.4	2.365	95.9 ± 5.0	0.280 ± 0.015	218 ± 17	1.64 ± 0.13
L21	32.6	76.9	2700	1	9.655	0.365	326		217 ± 15	0.304 ± 0.021	326 ± 16	2.37 ± 0.12
L24	32.5	77.0	2985	0.86	30.194	0.350	13.4	1.594	106 ± 5	0.082 ± 0.004	326 ± 16	0.500 ± 0.024
L25	32.5	77.0	2985	0.93	19.985	0.346	20.0	2.025	80.1 ± 4.8	0.093 ± 0.006	162 ± 54	0.451 ± 0.151
L26	32.5	77.0	3050	0.89	11.207	0.370	193		201 ± 8	0.444 ± 0.019	589 ± 28	2.53 ± 0.12
L27	32.5	77.0	2975	0.84	20.236	0.354	123		356 ± 16	0.416 ± 0.019	917 ± 37	2.52 ± 0.10
L28	32.5	77.0	3000	0.90	29.992	0.354	55.0		484 ± 16	0.382 ± 0.012	1823 ± 256	2.24 ± 0.31
L29	32.5	77.0	2985	0.97	29.471	0.358	8.26	2.019	493 ± 13	0.401 ± 0.011	1256 ± 66	2.21 ± 0.12
L31	32.5	77.1	3020	0.98	29.815	0.353	58.2		451 ± 12	0.357 ± 0.009	1535 ± 72	1.99 ± 0.09
L32	32.5	77.1	3020	0.96	9.345	0.363	170		212 ± 13	0.552 ± 0.034	894 ± 45	3.40 ± 0.17
L33	32.5	77.1	3036	0.98	24.331	0.368	493		616 ± 17	0.624 ± 0.017	320 ± 16	3.52 ± 0.18
L37	32.4	77.6	4555	1	20.052	0.353	842		1081 ± 23	1.273 ± 0.034	364 ± 18	6.83 ± 0.35
L40	32.4	77.6	4780	1	16.367	0.368	216		846 ± 23	1.272 ± 0.035	1485 ± 88	7.16 ± 0.42
L41	32.4	77.6	4770	1	20.019	0.352	41.7	1.744	1147 ± 28	1.348 ± 0.033	2682 ± 88.5	7.90 ± 0.26
L42	32.4	77.6	4890	1	6.563	0.369	232		370 ± 15	1.391 ± 0.056	1681 ± 77	8.70 ± 0.40
L44	32.4	77.6	4070	0.99	18.571	0.339	69.2	0.783	628 ± 18	0.766 ± 0.022	1813 ± 65	4.56 ± 0.16
L48	32.4	77.6	4045	0.99	20.291	0.350	33.0	1.553	12.2	¡0.01±	17.0 ± 6.9	0.043 ± 0.017
L49	32.4	77.6	4190	0.99	30.022	0.345	11.5	1.983	1134 ± 29	0.872 ± 0.022	2823 ± 88	5.01 ± 0.16
L50	32.4	77.6	4070	0.99	20.065	0.353	18.5	2.003	776 ± 20	0.912 ± 0.023	1971 ± 62	5.34 ± 0.17

are probably more representative of the time of glaciation. Most of the boulders within such moraines have been heavily eroded when they were first entrained in the ice, as the result of plucking or quarrying by mass movement processes and/or by abrasion during glacial transport (Scott, 1992). It is anticipated that these boulders will have no inherited cosmogenic radionuclides. However, we have, whenever possible, sampled several boulders from each moraine to verify this assumption.

Exposure ages on boulders lodged on the crests of drumlins represent deglaciation times, as they are deposited subglacially and exposed only after the glaciers had retreated. The boulders on the crests of drumlins exhibited typical glacial shapes (Boulton, 1978), indicating that they are subglacially and englacially abraded (Fig. 2A). They should, therefore, have no inherited cosmogenic radionuclides. Cosmogenic ^{10}Be and ^{26}Al from boulders on ice-polished bedrock and from samples of the polished bedrock surfaces provide younger limits for the time of deglaciation. The exposure ages may appear younger than the time of deglaciation if the surface was covered with a thick layer of till for a significant period of time.

The sampling sites for cosmogenic radionuclide dating were selected in order to exemplify age differences between the glacial stages. Samples for the Kulti and Batal Glacial Stages were collected from locations along the Chandra valley (Plate 1 and Table 2). Chandra Glacial Stage surfaces and moraines are present at several locations along the Chandra Valley, but were inaccessible either because they occur above steep treacherous rock faces or because access was restricted by impassable rivers. The only accessible location in which samples could be collected from the Chandra Glacial Stage was above 4600 m a.s.l. on the Kunzum La (Plate 1).

Care was taken to avoid sampling below steep slopes where younger boulders could have fallen on to moraines after their formation or where substantial erosion, slope failure or human activity may have recently exhumed boulders. The exact location of each sample was recorded using a hand-held global positioning system. Skyline profiles were measured to allow correction for topographic shielding by surrounding mountain slopes.

The samples were crushed and sieved to a uniform size of 250–500 μm. Clean quartz was separated from the rocks by a chemical isolation method (Kohl and Nishiizumi, 1992) using HCl and HF–HNO_3 baths. An aliquot of the dissolved sample was used to determine the aluminum content using atomic absorption spectroscopy. Beryllium carrier, and stable aluminum carrier when appropriate, was added to the clean quartz separates and the sample was then dissolved in an HF–HNO_3 mixture. Beryllium-10 ($t_{1/2} = 1.5$ Ma) and ^{26}Al ($t_{1/2} = 0.705$ Ma) AMS measurements were carried out at the Lawrence Livermore National Laboratory (LLNL) Accelerator Mass Spectrometry (AMS) facility (Davis *et al.*, 1990).

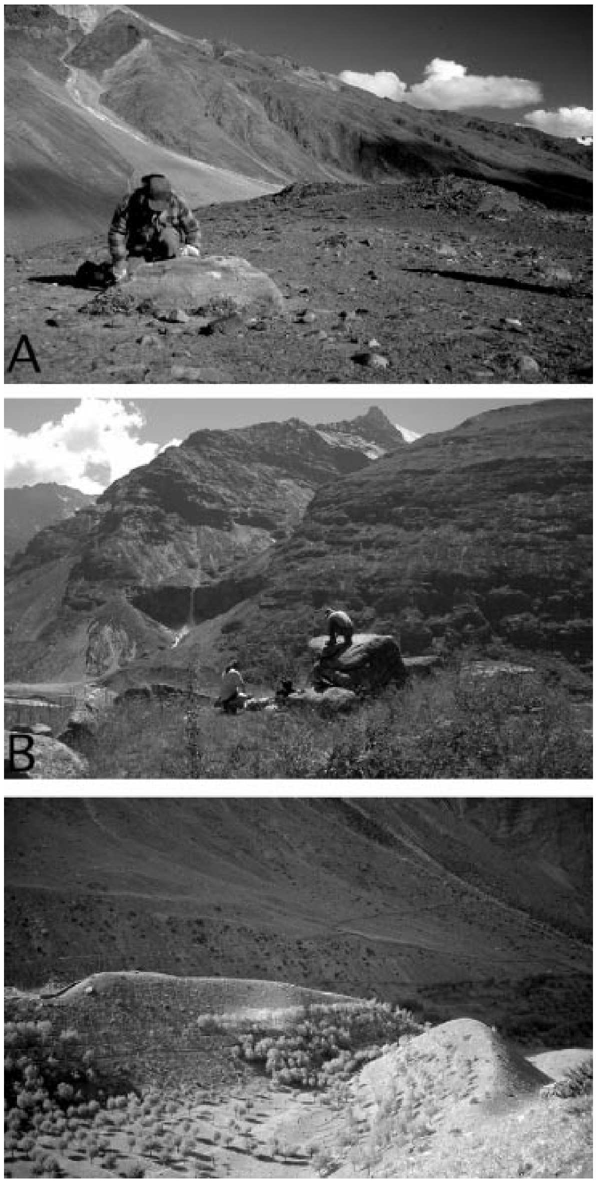

Figure 2 Glacial landforms in the Lahul Himalaya. (A) A drumlin near Chandra Tal with a lodge boulder on its crest. (B) View looking south across the Chandra river at Sissu Nala. The large boulder (sample L32) is on a lateral moraine of the Batal Glacial Stage. The high glacially eroded slopes in the middle ground were produced when a large valley glacier occupied the Chandra valley during the Batal Glacial Stage. (C) View looking southeast at the end moraine of Kulti Glacial age in Muling Nala. Samples L28 and L29 where collected from the crest of the southernmost moraine

Results and discussion

Tables 2 and 3 list the cosmogenic radionuclide ^{10}Be and ^{26}Al data and ages, the location and type of sampling sites and the relative age of each sample derived from morphostratigraphy. The ages presented in Table 3 are derived as discussed above.

The availability of numerical ages has led us to reinterpret several of Owen *et al.*'s (1996, 1997) relative ages, and Table 3 provides appropriate explanations. The agreement in exposure ages between multiple samples collected on individual surfaces is good, suggesting that inheritance of cosmogenic radionuclides is not a significant factor. This agreement also provides a measure of confidence that the moraine surfaces were not altered significantly and that moraine formation marks well-constrained periods of glacial advance.

Chandra Glacial landforms

Although samples were collected from surfaces believed to represent the Chandra Glacial cycle, in fact no samples representing this stage were dated. Exposures of the Chandra

Table 3 Sample descriptions and cosmogenic radionuclide dates

Sample Number	Altitude (m)	Location	Sample Type[1]	Relative Age[2]	Exposure Age (ka)[3,4,5]			Mean with geomagnetic correction	$^{26}Al/^{10}Be$ age ratio	Notes[7]
					^{10}Be	^{26}Al	Mean[6]			
L7	4340	32°28.397′/77°36.847′ Chandra Tal	D	B	11.8 ± 0.8	10.7 ± 0.7	11.2 ± 0.5	11.4 ± 0.8	0.91	
L8	4350	32°28.781′/77°36.766′ "	D	B	14.1 ± 0.5	13.6 ± 0.7	14.0 ± 0.4	14.0 ± 0.4	0.97	
L9	4350	32°28.781′/77°36.768′ "	D	B	13.3 ± 0.6	13.8 ± 0.4	13.7 ± 0.3	13.7 ± 0.5	1.05	
L10	2390	32°18.913′/77°09.355′ Solang Nala	L	K	11.5 ± 0.9	13.7 ± 1.4	12.1 ± 0.8	12.2 ± 1.6	1.19	
L12	2415	32°18.962′/77°09.308′ "	L	K	10.5 ± 0.3	10.4 ± 0.6	10.5 ± 0.3	10.6 ± 0.3	1.00	
L15	2430	32°18.988′/77°11.468′ Rohtang Pass	H	B	15.7 ± 0.5	1.4 ± 0.09	15.8 ± 0.5	15.5 ± 0.5	0.09	g, h
L20	2865	32°36.124′/76°55.412′ Rape	L	K (B)	8.8 ± 0.5	8.7 ± 0.7	8.8 ± 0.4	9.0 ± 0.4	0.98	d
L21	2700	32°36.200′/76°55.377′ "	L	K (B)	9.6 ± 0.7	12.5 ± 0.6	11.2 ± 0.5	11.3 ± 2.1	1.31	d
L24	2985	32°31.200′/76°57.859′ Muling Nala	L	K	2.5 ± 0.1	2.5 ± 0.1	2.5 ± 0.1	2.8 ± 0.1	1.01	a, b
L25	2985	32°31.200′/76°57.833′ "	L	K	2.6 ± 0.2	2.1 ± 0.7	2.6 ± 0.2	2.9 ± 0.4	0.81	a, b
L26	3050	32°31.481′/76°57.843′ "	L	B	12.8 ± 0.5	12.2 ± 0.6	12.5 ± 0.4	12.6 ± 0.4	0.95	a
L27	2975	32°31.693′/76°57.872′ "	L	B	13.1 ± 0.6	13.3 ± 0.5	13.3 ± 0.4	13.3 ± 0.4	1.01	a
L28	3000	32°31.470′/76°57.627′ "	L	K	11.2 ± 0.4	10.9 ± 1.5	11.2 ± 0.4	11.3 ± 0.4	0.98	a
L29	2985	32°31.498′/77°57.664′ "	L	K	10.9 ± 0.3	10.1 ± 0.5	10.8 ± 0.3	10.9 ± 0.6	0.92	a
L31	3020	32°29.008′/77°07.751′ Sissu Nala	L	B (K)	9.4 ± 0.2	8.8 ± 0.4	9.3 ± 0.2	9.5 ± 0.5	0.93	a, e, b
L32	3020	32°28.983′/77°07.681′ "	L	B (K)	15.0 ± 0.9	15.3 ± 0.8	15.2 ± 0.6	14.5 ± 0.6	1.03	a, e
L33	3036	32°29.002′/77°07.744′ "	L	B (K)	16.4 ± 0.4	15.4 ± 0.8	16.1 ± 0.4	15.8 ± 0.6	0.94	e, a
L37	4555	32°23.547′/77°37.216′ Kumzum La	L	B	14.7 ± 0.4	13.2 ± 0.7	14.3 ± 0.3	14.3 ± 1.1	0.90	
L40	4780	32°23.947′/77°37.373′ "	I	B (C)	13.2 ± 0.4	12.5 ± 0.7	13.1 ± 0.3	13.2 ± 0.6	0.94	c
L41	4770	32°23.868′/77°37.436′ "	P	B (C)	14.1 ± 0.4	13.8 ± 0.5	14.0 ± 0.4	14.0 ± 0.4	0.98	c, h
L42	4890	32°23.979′/77°37.408′ "	P	B (C)	13.8 ± 0.6	14.4 ± 0.7	14.0 ± 0.7	14.0 ± 0.6	1.05	c, h
L44	4070	32°21.638′/77°36.738′ Batal	L	K (B)	11.2 ± 0.3	11.2 ± 0.4	11.2 ± 0.3	11.4 ± 0.3	1.00	e
L48	4045	32°21.832′/77°36.487′ "	L	SII	¡209	0.1 ± 0.04	0.1 ± 0.04	0.1 ± 0.04	0.51	f, i
L49	4190	32°21.562′/77°37.055′ Batal	L	B (K)	12.1 ± 0.3	11.6 ± 0.4	11.6 ± 0.2	12.0 ± 0.4	0.96	e
L50	4070	32°21.633′/77°37.031′ "	L	B (K)	13.5 ± 0.3	13.3 ± 0.4	13.4 ± 0.3	13.5 ± 0.3	0.98	e

1. D—lodged boulder on the crest of a drumlin. L—lodged boulder on the crest of a latero-frontal moraine. H—boulder on the crest of a hummocky moraine. I—ice-polished bedrock surface. P—perched boulder on ice-polished bedrock surface.
2. Owen *et al.*'s (1997) original glacial stage is shown in parenthesis where the relative ages of moraines have been reinterpreted. SII—Sonapani II Glacial Stage. K—Kulti Glacial Stage. B—Batal Glacial Stage. C—Chandra Glacial Stage.
3. The measured ratios were normalized to ICN ^{10}Be and NIST ^{26}Al standards prepared by Nishiizumi (private communication).
4. Minimum exposure ages are calculated as described in the text.
5. The stated uncertainties reflect errors in the AMS measurement and the error attendant with the AA determination of the Al concentration. The errors do not reflect uncertainties in the production rates either from production rate changes as a function of time or uncertainties in the production rate determination. Further discussion is given in the text.
6. The mean is weighted according the uncertainty of the ^{10}Be and ^{26}Al ages. The uncertainty is the larger of the uncertainty in the weighted mean and the standard deviation of the two ages.
7. a—shielding correction has been made because of an obscured skyline (≥20°). b—The surfaces of these boulders are exfoliated and the younger ages may be the consequence of deep weathering that removed the surface layers revealing deeper rock that has was only recently exposed to cosmic rays. c—The surfaces and boulders on which these samples were collected were thought by Owen *et al.* (1997) to have been glaciated only during the Chandra Glacial Stage. However, the young ages and the freshness of the surfaces and boulders suggest that ice may have overtopped the ridges at this location during the Batal Glacial Stage. d—Owen *et al.* (1997) attributed these moraines to the Batal Glacial Stage because of their low altitude. However, like Kulti Glacial moraines in the upper valley, these moraines extend only a few hundred meters into the main valley. The former glacier had a source on the northern slopes of the Pir Panjal and may have been fed by snow blow processes and avalanching from north facing cornices. This may have helped lower the glacier's equilibrium line altitude to allow the glacier to extend to low altitudes. e—Owen *et al.* (1995) thought the moraines at Sissu were produced during the Kulti Glacial Stage because they did not extend into the main valley. However, these moraines are several hundred meters above the valley floor and can easily been attributed to the Batal Glacial Stage. e—The glacial chronology is reinterpreted here on the basis of morphostratigraphy. The moraines of the Batal Glacial Stage are lowest in the valley and the moraines of the Kulti Glacial stage are built up on the debris of Batal moraines (see Fig. 1A). f—The concentrations of ^{10}Be and ^{26}Al in this sample is very low because of the young age, therefore, calculating the errors and means for this sample is not very meaningful. g—the low ^{26}Al date may be due to an undetermined analytical problem. h—^{26}Al is anomalously low, and was not included in the average age calculations. i. ^{10}Be age could not be determined and was not included in the average age calculations.

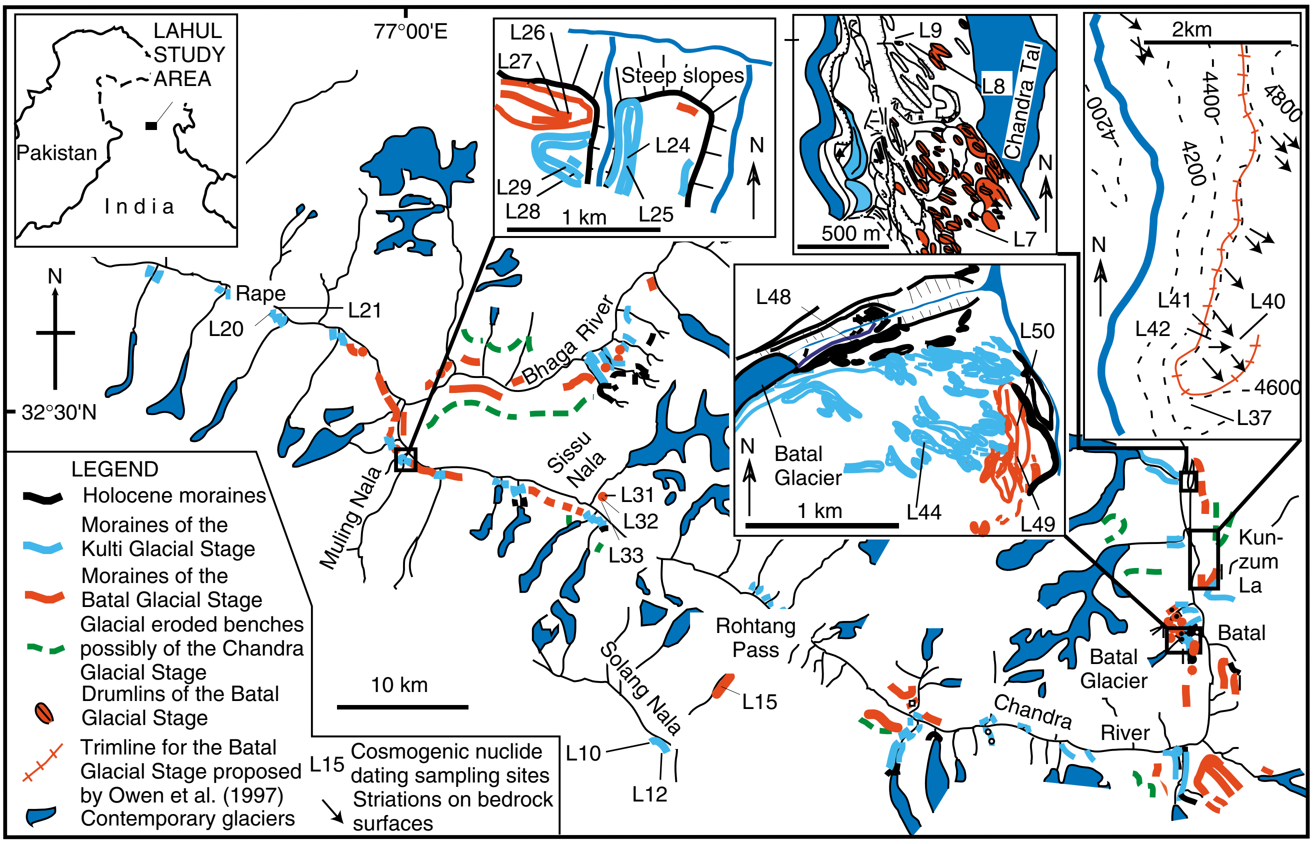

Plate 1 Geomorphological maps showing the study areas and the main moraines, and locations of the samples that were dated in this study

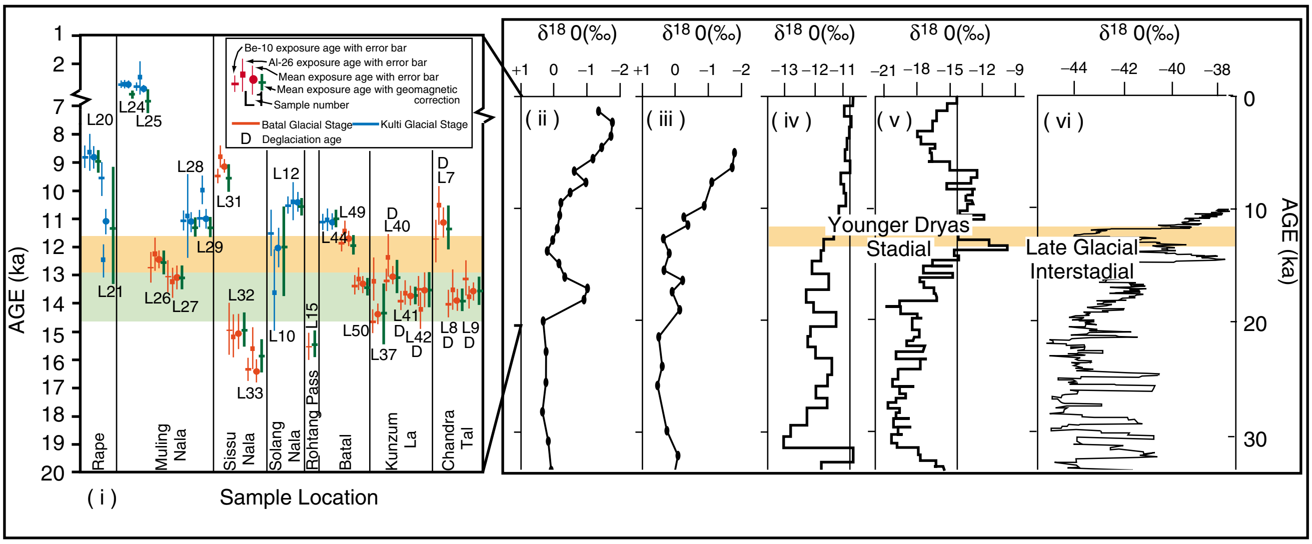

Plate 2 Comparison of the cosmogenic radionuclide dates for deglaciation in the Lahul Himalaya (i) with δ^{18}O data from (ii) *Globigerinoides sacculifer* in core SK-20-185 from the East Arabian Sea (Sarkar *et al.*, 1990), (iii) *Globigerinoides sacculifer* in core CD-17-30 off the coast of the Oman (Sarkar *et al.*, 1990), (iv) the Dunde Ice Cap core in Tibet (Thompson *et al.*, 1989), (v) the Guliya Ice Cap core in Tibet (Thompson *et al.*, 1997) and (vi) the Summit ice core in Greenland (Dansgaard *et al.*, 1993). The orange and green horizon bands show the duration of the Younger Dryas Stade and Late-glacial Interstadial, respectively. Note that the data in parts (ii) and (iii) are plotted against radiocarbon years whereas the other data are plotted against calendar years

age surfaces may be present along the Chandra valley, but their locations made it impossible for us to collect samples.

Batal Glacial landforms

The boulders and surfaces from the Kunzum La were presumed to be of Chandra age. However, the exposure ages for samples from the Kunzum La are between ca. 13.2 and 14.3 ka, similar to dates for the landforms associated with the Batal Glacial Stage. The interpretation of Owen *et al.* (1997) that these deposits are of Chandra Glacial age is incorrect. It is likely that glacial ice overtopped the high glaciated surfaces in the upper Chandra valley during the Batal Glacial Stage, eroding fresh bedrock surfaces and depositing glacial boulders. Samples were collected from these glacially polished bedrock surfaces and a boulder perched upon the bedrock. These latter samples are exposed after deglaciation. The similarity in exposure ages between these and the boulders on moraine crests suggests that the lateral moraine formed shortly before deglaciation.

Surface exposure ages of boulders from moraines and drumlins, and glacially polished bedrock surfaces of the Batal Glacial Stage cluster between ca. 12 and 15.5 ka (Tables 2 and 3, and Plate 2). There are no discernable differences between the ages for samples collected from latero-frontal moraines, drumlins and ice-polished bedrock. This suggests that the uppermost parts of latero-frontal moraines of Batal Glacial age formed shortly before deglaciation and represent the final stages of moraine formation. From these data we cannot determine how long the extensive valley glacier system of the Batal Glacial stage existed in the Lahul Himalaya. However, it is likely, given the thickness of the moraines and the large drumlin fields, that the Batal Glacial Stage may have reached its maximum substantially earlier than 15.5 ka. The Greenland ice-core data suggests that the Late Glacial Interstadial occurred between ca. 12.8 and 14.6 ka (Dansgaard *et al.*, 1993: Plate 2, part vi). The cosmogenic radionuclide data, therefore, indicate that ice was present in the valley during this period, but marginally older dates on some of the moraines may help to support the view that glaciers also may have existed in the Batal valley prior to the Late-Glacial Interstadial. The Guliya and Dunde ice-core data indicate that glaciers in Tibet were still substantial during the Late-Glacial Interstadial (Bølling/Allerød) (Plate 2, parts iv and v). This circumstance supports our conclusions that glaciers were still producing moraines in the Lahul Himalaya during the Late-Glacial Interstadial.

The exposure ages of samples associated with the Batal Glacial Stage indicate that this glacial cycle is much younger than was previously thought. The cosmogenic radionuclide exposure ages of the Batal Glacial Stage conflict with Owen *et al.*'s (1997) OSL dates of 43.4 ± 10.3 ka and 36.9 ± 8.4 ka. The samples used for this analysis are deltaic sediments believed to be associated with the deglaciation of the Batal Glacial Stage. Coxon *et al.* (1996) suggested that these deltas formed at the mouths of rivers feeding an ice-dammed lake. When the dam forming the lake was breached, a catastrophic flood left deposits along the Chandra valley. However, the freshness of the bedforms and boulders within the flood deposit suggests that the deposits are less than a few thousand years in age. Old OSL dates are at variance with recent deposition of these sediments. The older OSL ages might be explained if the sediments were only partially bleached. Deglaciation after ca. 17 ka also is supported by the work of Singh and Agrawal (1976), whose radiocarbon dates on lacustrine sediments in Kashmir Basin show that deglaciation was occurring in Kashmir at ca. 14 000–15 000 ^{14}C yr BP (ca. 16 000–17 000 cal. yr BP). The agreement between exposure ages and the radiocarbon ages leads us to conclude that the OSL ages of Owen *et al.* (1997) are anomalously old, most likely the result of partial bleaching.

Kulti Glacial landforms

The cosmogenic radionuclide dates on latero-frontal moraines of the Kulti Glacial Stage show that a minor glacial advance occurred during the early Holocene at between ca. 10.6 and 11.4 ka (Plate 2, part i). Owen *et al.*'s (1997) radiocarbon date of 9160 ± 70 yr BP (10 224–10 313 cal. yr BP: Stuiver *et al.*, 1998a,b) from the base of a peat bog within moraines of the Kulti Glacial Stage (Table 1) supports the view that climatic amelioration had occurred by ca. 10 ka (calendar years). The cosmogenic radionuclide dates on the Kulti moraines show that there was a relatively short period (ca. 1000 yr) between deglaciation of the Batal Glacial Stage glaciers and the advance of Kulti Glacial Stage glaciers (Plate 2, part i). The difference in landform types associated with the Batal Glacial Stage (eroded large lateral and latero-terminal moraines, and drumlins) and Kulti Glacial Stage (small sharp-crested end moraines) suggest that the Kulti Glacial Stage does not represent a readvance of glaciers of the Batal Glacial Stage, but was a distinct glaciation that occurred during the early Holocene (Fig. 2). In addition, the relatively small size of the Kulti Glacial moraines suggests that this glaciation probably lasted only for a short time (hundreds to a few thousands years).

Based on the currently accepted cosmogenic radionuclide production rates, it is likely that there was not a glacial advance in the Lahul Himalaya during the Younger Dryas Stade.

To the north of Lahul, in the Zanskar Range, Taylor and Mitchell (2000) recognized three glacial stages and a minor advance that they correlated with the Chandra, Batal, Kulti and Sonapani Glacial Stages in the Lahul Himalaya. Optically simulated luminescence methods yielded a date of 78.0 ± 12.3 ka on moraines that mark the maximum position of Batal age glaciers and a date of 40.0 ± 9.3 ka on sediments that post-date the Batal Glacial Stage. Taylor and Mitchell (2000) also determined ages of 16.2 ± 5.6 ka and 12.2 ± 4.8 ka on glaciofluvial sediments that mark the maximum position of the Kulti age glacier. Furthermore, they dated a recessional and a late stage landform of the Kulti Glacial Stage at 13.1 ± 4.9 ka and 10.2 ± 2.1 ka, respectively. These dates contrast with the cosmogenic radionuclide exposure ages on samples from the Kulti and Batal glacial landforms and highlight the danger of extending correlations based on morphostratigraphy and relative weathering across distant areas of the Himalaya. Owen *et al.* (1997) showed that relative weathering characteristics of moraines of similar age vary considerably across the Lahul Himalaya. Furthermore, Burbank and Fort (1985) showed that the relative weathering and morphology of moraines in Ladakh are controlled not only by age, but also by altitude and microclimatic variations. It therefore is likely that Taylor and Mitchell's (2000) correlation of moraines in Zanskar with those in Lahul is in error.

On the basis of oxygen isotope data from deep-sea sediments in the Arabian Sea and off the coast of Oman, Gupta *et al.* (1992) hypothesised that during the period between 16 000 and 20 000 ^{14}C yr BP (ca. 19–24 ka), glacier meltwaters originating in the Himalayas and Tibet increased in volume as a result of accelerated melting of mountain glaciers. Plate 2 (parts i, ii and iii) provides a comparison of these data. From the surface exposure dates we infer that the timing of Batal deglaciation occurred at the latest part of the Late-glacial Interstadial (Bølling/Allerød), significantly later than proposed by Gupta *et al.* (1992). Our ages of the Batal deglaciation remain much younger than the deglaciation proposed by Gupta *et al.* (1992). The oxygen isotope minimum observed by Gupta *et al.* (1992) may not in fact be indicative of meltwater input, but rather may reflect the contribution of increased monsoon rainfall over the ocean.

These data suggest that glaciation in the Lahul Himalaya has occurred during warm intervals, that is, during the Late-glacial Interstadial (Bølling/Allerød) following the Older Dryas Stade and during the early Holocene following the Younger Dryas Stade. Using pollen and foraminiferal concentrations in sediment cores from the Arabian Sea, Overpeck *et al.* (1996) showed that upwelling was enhanced at about 14.7–15.3 ka and then again at 10.8–11.5 ka, which they attributed to an intensification of the South Asian summer monsoon. These intensification events were also demonstrated from the $xs^{231}Pa/xs^{230}Th$ ratio data derived from the western Arabian Sea core 74KL (Marcantonio *et al.*, 2001). Using luminescence dating of sediments in the Thar desert, Kar *et al.* (2001) showed that the period between 13 and 8 ka was a time of major climatic instability induced by variations in the South Asian summer monsoon. Furthermore, on the basis of lake-core and shoreline studies, Gasse *et al.* (1991) showed that the early–middle Holocene and Late-glacial Interstadial were warm and humid in western Tibet. These studies help support the view that an intensified monsoon was dominant, when glaciers were growing in the Lahul Himalaya during the Kulti and Batal glaciations. During these periods of increased insolation, the South Asian summer monsoon strengthened and/or extended its influence further north and west than at present (Clemens *et al.*, 1991; Emeis *et al.*, 1995). The resulting enhancement in summer snowfall at high altitude presumably resulted in a positive mass-balance and caused glaciers to advance.

The timing of glaciation in the Lahul Himalaya contrasts with the results of work in some other parts of the Himalayas. In Swat and around Nanga Parbat, for example, the most extensive glaciation occurred earlier than marine oxygen isotope stage 2, between ca. 35 and 65 ka (Sloan *et al.*, 1998; Phillips *et al.*, 2000; Richards *et al.*, 2000a). In Garhwal, to the southeast of Lahul, Sharma and Owen (1996) provide evidence and OSL dates to show that the local last glacial maximum occurred at ca. 63 ka, with more restricted glaciation at ca. 18 ka. These differences with the Lahul results are too large to be explained by uncertainties in cosmogenic radionuclide production rates. It is possible that glaciers in Lahul were more extensive during earlier parts of the last glacial cycle, but evidence for this may have been destroyed during subsequent reworking of glacigenic sediments. In the Khumbu Himal, Nepal, Richards *et al.* (2000b) dated three glacial stages using OSL: the Periche Glacial Stage (ca. 18–25 ka), the Chhukung Glacial Stage (ca. 10 ka) and the Lobuche Glacial Stage at (ca. 1–2 ka). Deglaciation following the Periche Glacial Stage may be coincident with the Batal deglaciation. The Chhukung Glacial Stage is at present poorly constrained. The dates available apparently mark the end of an important episode of glacier thickening (Richards *et al.*, 2000b). It thus is possible that the Chhukung and Kulti Glacial Stage are synchronous, but further work is necessary to test this hypothesis.

The cosmogenic radionuclide exposure ages on glacial landforms in the Lahul Himalaya support Benn and Owen's (1998) hypothesis that glaciation in some areas of the Himalayas is dominated by oscillations in the South Asian summer monsoon and likely asynchronous with oscillations in Northern Hemisphere ice-sheets and oceans.

Conclusions

Cosmogenic radionuclide ^{10}Be and ^{26}Al ages for boulders on the crests of moraines and drumlins, and for bedrock from ice-polished surfaces constrain the timing of glaciation during Late Glacial and early Holocene times in the Lahul Himalaya. These data show that moraines belonging to the Batal Glacial Stage were formed between ca. 12–15.5 ka during the Late-glacial Interstadial (Bølling/Allerød) and that deglaciation at the end of the Batal Glacial Stage was completed by ca. 12 ka. These data also show that the moraines of the Kulti Glacial Stage formed shortly (ca. 1000 yr) after the Batal Glacial Stage during early Holocene times at ca. 10–11.4 ka. This suggests that positive mass-balances existed for glaciers in the Lahul Himalaya during periods of increased insolation when the South Asian summer monsoon was strengthened and/or extended its influence further north and west to enhance summer snowfall at high altitudes. The observed glaciations in the Lahul Himalaya correlate well with the South Asian summer monsoon. There is no evidence of a glacial advance synchronous with changes in Northern Hemisphere ice-sheets and oceans, but a later and more extensive Batal advance could have destroyed evidence for this. These conclusions have interesting environmental implications, and they suggest that glaciers in this part of the Himalayas initially may grow if global temperatures increase and the monsoon becomes intensified as a result of greenhouse warming induced by human or natural processes. These new dates show unequivocally that the Batal and Kulti Glacial Stages are significantly younger than was thought previously.

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